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An innovative approach to mine blast fragmentation management using complexity analysis: three case studies

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Abstract

This paper introduces an innovative solution for devising a robust blasting plan that will present consistently good fragmentation performance under highly uncertain environments. The analysis will be carried out using complexity analysis tools, a model-free approach to complex systems which is particularly well suited to the problem of finding non-deterministic dependencies between multiple variables. The study is backed-up by data from over 2,000 blast records from Brazilian mines and identifies what are the critical aspects of the system and how to manage the blasting plan to reduce their impact on its performance.

1 Introduction

Rock fragmentation due to blasting operations is the key result of aggregates and ore mining activity before plant treatment. It has been observed in many case studies (Clerici et al., 1974; Ryu et al., 2009; Sastry and Ram, 2004) that power consumption of loading machinery and primary crushers, operating either in pit or at the plant, decreases with a higher ratio of fragmentation obtained from the blast. On the other hand, a lower ratio of fragmentation decreases the primary blasting costs (Ryu et al., 2009). Clerici et al., 1974, Ryu et al., 2009, Sastry and Ram, 2004 and Božić, 1998 agree that poor fragmentation results lead to:

- increased secondary blasting
- increased rate of muck shovel loading
- increased difficulty in transport
- increased energy consumption at crushing or milling
- low crusher or mill performances

On the other hand, when operating on fragmentation results in order to reduce secondary blast or other kind of secondary fragmentation before crushing, primary blast costs and drilling costs increase (Ryu et al., 2009), making the efficiency of the mine site workings decrease. When secondary blasting is avoided or reduced to its minimum in order to increase mine site working efficiency, the spared block dimension reduction cost is transferred to crushing or milling, reducing their efficiency and increasing its costs.

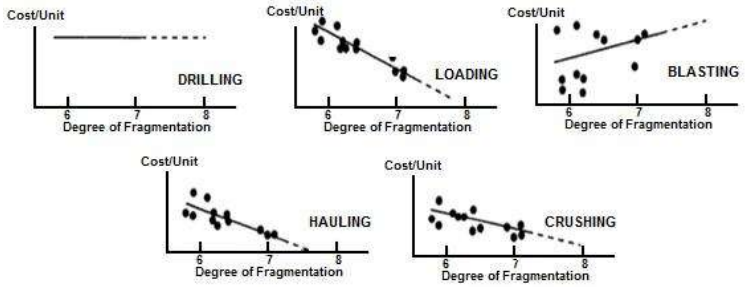

FIGURE 1: Effect of degree of fragmentation on individual unit operation costs and overall cost (MacKenzie, 1967)

Mackenzie (1967) is nowadays a classical analysis that showed how increasing rock fragmentation decreases loading, hauling and crushing costs while at the same time increases drilling and blasting costs (see Fig.1).
Generally speaking, an *optimum* situation should be found at the intersection of McKenzie´s decreasing and increasing site laws of cost. The problem with this approach is that geological conditions are source of a high level of uncertainty. In practical situations, due to geostructural conditions (Chakraborty et al., 2004; Grenon et al., 1998; Lu and Latham, 1998), site laws of cost, and hence *optimum* conditions, vary from bench to bench. Nevertheless, in order to achieve industrial productivity levels in mining, a pre-defined blast design performed at the beginning of operations

should require minimal adjustments from blast to blast along the operations deployment.
This paper proposes an innovative approach to the solution of the blasting problem, as an alternative to the traditional blasting optimization techniques. These optimization techniques include highly sophisticated mathematical models, such as the one proposed by Berta (1985), whose high fragility due to great inter-dependency of its variables has already been discussed in Seccatore et al. (2010).

2 Critical variables for blast fragmentation management

A blast in open pit mining has several variables that can contribute to its results in terms of fragmentation. These variables can be classified in terms of geometry of bench and drilling, explosive charge, initiation system and rock qualities (see Table 1). Chakraborty et al. (2004), Lu and Latham (1998), Mancini and Cardu (2001) and Thornton et al. (2002) agree with a similar classification.

TABLE 1: Variables of the blast

GEOMETRY	EXPLOSIVE CHARGE	INITIATION SYSTEM	ROCK
Drilling diameter	Explosive type(s)	Initiation system(s)	Type of rock
Number of holes	Explosive(s) density	Number of detonators	Rock mass structure
Number of rows	Bottom Charge	Delays	Rock stress resistance and Modula
Bench Height	Column Charge	Charge per delay	Rock acoustic impedance
Burden	Specific Charge		
Spacing	Coupling ratio		
Hole length			
Underdrilling			
Stemming			
Inclination			

Fragmentation is a “process of transition from in-situ to blasted block size resulting from the application of explosive energy” (Lu and Latham, 1998). Many case studies (Chakraborty et al., 2004; Grenon et al., 1998; Lu and Latham, 1998) focused on the predictability of blasted block sizes depending on the natural sizes of the blocks in the rock mass due to the structure of natural joints, discontinuities and fractures.
The action of fragmentation of the explosive energy on the rock has been widely recognized, e.g. Berta (1985) and Moser (2008), as related to the specific energy [MJ/m3] of the blast and to the specific surface [m2/m3] of the obtained fragmented rock.

Many other studies, e.g. Clerici et al. (1974) and Moser (2008), have also shown that the results of fragmentation are largely dependent on the specific charge of explosive [kg/m3].
An approach to understand the interdependencies between all these variables will be carried out through Complexity Analysis tools, by means of an innovative graphical pattern recognition method, where neither approximation nor linear regression models are applied to the data, allowing taking into account also the a-typical set of data normally considered as outliers.

3 Complexity analysis

Engineering systems can be seen as transformations of input data into elaborated output results through particular types of flow, being subject to complexity analysis just like any other system. The two key components of the complexity metric used in this analysis are the so-called System (or Complexity) Map – which reflects how information flows within a system; its structure – and entropy, which measures the degree of disorganization in the system. These components are retrieved from the system by means of a model-free technology, meaning there is no imposition of analytical models on top of data. The advantage of such approach is the elimination of subjectiveness in the analysis, as models invariably require assumptions and introduce additional uncertainty into a problem. Thus, in the present case, regression models, response surfaces, neural nets or statistics will give way to an innovative approach which identifies structure and patterns within multi-dimensional data, described below and illustrated in Figure 2.

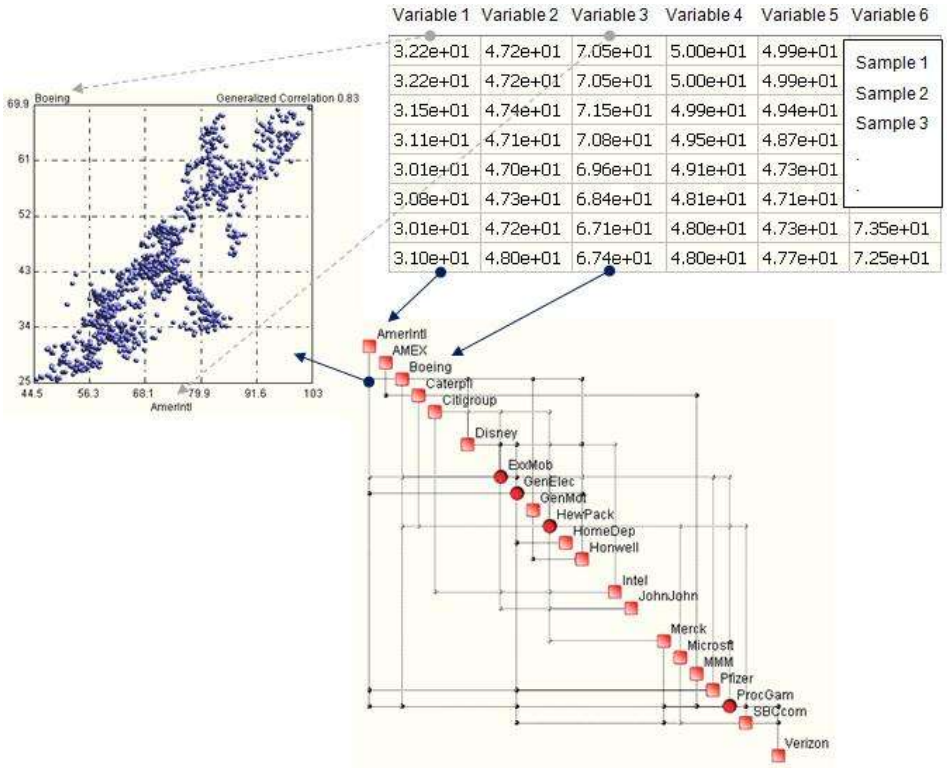

FIGURE 2: Input Data table, Scatter Plot and Process Map

The process of complexity computation is as follows:

- A rectangular array of data is provided (see Figure 2 – top right quarter), in which the columns represent particular variables while the rows correspond to samples.
- A software tool determines the existence of couplings - generalized correlations - between all possible pairs of variables, by analyzing their scatter plots, transformed in two dimensional images (see Figure 2 – left-hand half), using pattern recognition algorithms.
- A System Map (see Figure 2 – lower half), which illustrates by means of a graph the topology of the relationships, is constructed.

The map is composed of:

- nodes, which correspond to the variables and which are aligned along the diagonal of the map. The order of the nodes in the map is the same as that in the data array.
- links, which correspond to couplings between nodes, indicated by means of connectors (see orange dots in map).

Complexity is computed as a function of the map's structure and of the nature of the couplings between the variables. In the event a variable does not have any significant coupling with any of the other variables, it is indicated in the System Map by means of an empty rectangle. Variables which possess the highest number of couplings - known also as degree - are known as hubs and are indicated by means of red discs.

Critical Complexity, which represents a threshold beyond which the system looses it´s resilience, is also computed. The difference between the system´s complexity and it´s critical complexity is a measure of the system's resilience, or robustness. This translates into how much uncertainty from the environment the system can cope with and still preserve its functionality. A system is considered "robust" if its output is not greatly or permanently affected by outliers and unexpected variations in input data.

Highly complex systems are more exposed to the effects of uncertainty because of the countless ways in which they process information. They can fail in many ways, often due to apparently innocent causes.

Thus, highly complex systems operating in highly uncertain environments are inherently fragile. Complexity C derives from the design. Uncertainties U derive from the realization and the work environment. Their combination leads to the fragility F of the system, which can be understood as its exposure to risk.

$$F_{\text{system}} = f(C_{\text{design}}, U_{manufacturing} + U_{\text{environment}})$$

Interpreting the above formula in our case:

- the *design* is the blast project, totally controllable
- the *manufacturing* are the drilling and charging operations, only controllable up to a certain level
- the *environment* is the local geological condition, not controllable

Since uncertainty in the environment (geology) cannot be avoided, it is of necessity to learn to live with it. Hence the need is to manage complexity through the design (blast project). A more detailed reading on the subject can be found in Marczyk (2006) and Marczyk (2008).

4 Optimization and robustness

When a system is optimized, its functionality is artificially specialized to work under specific conditions to produce a high-quality result. Its structure is stiff and highly dependent on inner and contour variables, and highly vulnerable under their variations and criticalities. An optimized system, in order to work well, needs an excellent knowledge of the values of its variables, both controllable such as production variables and uncontrollable such as environmental parameters.
When a system is robust, on the other hand, it is more flexible in its application, and possesses the capability to produce expected and acceptable results under varying or even unforeseen conditions. Robustness is a measure proportional to the distance between the operative and the critical complexity of a given system: in other words, it is inversely proportional to its vulnerability to uncertainties and criticalities, coming both from productive or environmental parameters.

5 Complexity analysis on mine blasting data

An initial test to see how C.A. analyzes blasting operations confirmed that this approach “allows a clear understanding of the correlations between the variables in blasting systems” Seccatore et al. (2010). C.A. has hence been applied to analyze the data from a campaign of over 2000 blast records in Brazilian mines. The campaign has been conducted in São Paulo (SP) and Rio Grande do Sul (RS) states, Brazil. The mines where analyses have been performed and the complexity results are reported in Table 2.

5.1 Mine 1 (Columnar Basalt Quarry)

The system has a high degree of entropy, in other words, there’s a high noise content in the information exchanged through the inter-connections.
The structure of the inter-connections between the variables of this system (see Fig.2) is ruled by the parameters of explosive loaded in the holes. The variables with the highest number of connections with the others are Column Charge and Charge per Delay. These critical variables are called HUBs: variables that are characterized by their characterized by their efficiency in propagating any variation of their values through the system.
The complexity of the system as well is ruled by the Column Charge parameter (ANFO charge). A variation of this value can lead to instability of the system. The total volume to be blasted (total volume of the blast, number of holes) is as well an influent variable in the complexity of the system.
The level of complexity of the system is close to its critical level. The robustness figure of the operations is a marginal 70%. Robustness figures above 80% are generally considered good. This not so good robustness figure, caused by the high

degree of disorder and inter-correlation, means that the system does not result steady: some variations in the operative conditions (execution of the drilling, of the loading and initiation line, or geological conditions different from usual) can lead to undesired and unexpected results, with problems affecting productivity and operations (bad fragmentation), environmental issues (noise and vibrations) or safety (flyrocks).

5.2 Mine 2 (Metamorphic Basalt Quarry)

In this mine it has been possible to analyze project data and real field data. This allowed a comparative analysis between required and obtained parameters of the blast.
The structural connections between the variables of the system appear quite strong and inter-correlated, both in the model and in the real data (see Fig. 3). The complexity levels of the two structures appear very close.

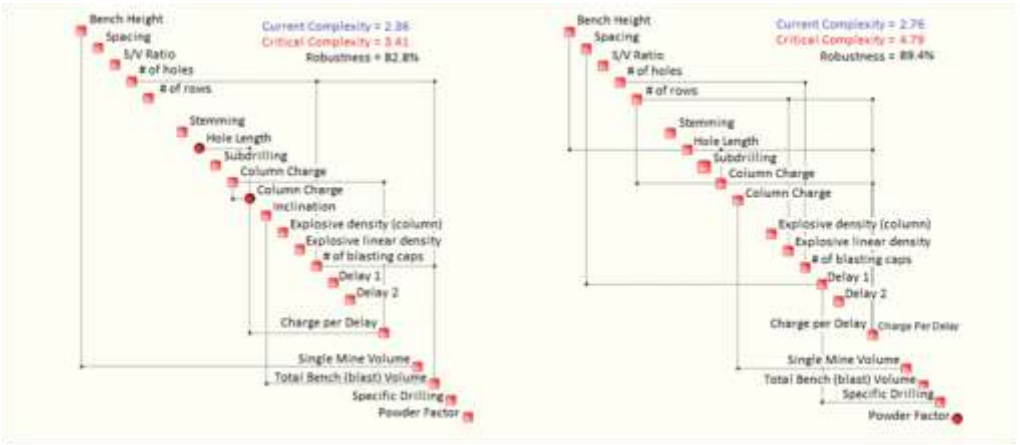

FIGURE 3: Sultepa´s Process Maps. Field data (left) and project data (right)

The complexity of these data is ruled more by the geometrical dimension of competence of each single hole (hole length, bench height, volume of competence) than by the charging parameters. In the general complexity, there's a clear influence from the longer of the delays chosen in the firing line.
In the project data, apart from the influence of the volume of competence of each mine, there's also significant contribution to total complexity from the charge per hole and from the charge shooting at the same delay.
It appears that, from the point of view of complexity, many of the parameters that influence the behavior of the whole system are common to both real and project data. This means a good structural accordance with the project during the preparation of the blast. What changes is the level of influence of the parameters. In the project intentions the structural dependency is focused on the choice of the quantity of explosive per hole and per delay. In the realization of the blast, instead, complexity depends mainly on the geometrical characteristics of the volume of competence of each hole.

5.3 Mine 3 (Coal mine)

The structural connections between the variables of the blast are weak. (see Figure 4). The hole depth and all the operational parameters relative to charging and stemming the hole itself appear at the center of the system´s structure of links. The only parameter relative to the blast as a whole is the maximum charge per delay that takes into account the shot of several holes at the same time. The geometry of the drilling pattern has no role in the general complexity of this working: neither the spacing between the holes, nor the shape of the grid (Spacing/Burden ratio). The complexity structure of the system is centralized around the single hole, and not on the entire blast as a whole.

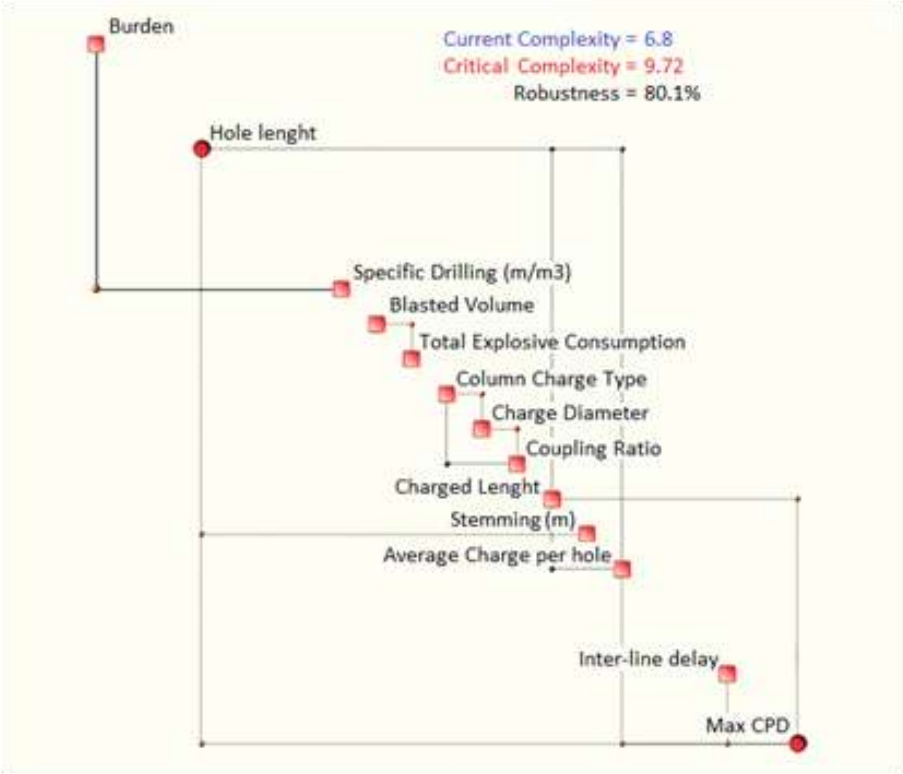

FIGURE 4: Copelmi´s Process Map

Being this a weak blasting work (see Table 2), meant to break the rock more than fragmenting and moving it, even the specific charge does not influence the other variables. Being a strip blasting of thin and wide layers, what mostly affects the structure is the delay between lines: the hole-to-hole delay does not even show in the system map.

The system has a very simple structure, with low number of links between the variables. Several variables do not contribute to the general complexity. This gives the system a relative inner robustness: the variation of some values does not greatly affect the general stability of the whole system. Hence, the complexity appears far below the critical value and the entire working results robust.

TABLE 2: Mines involved in the analysis

Mine	Geology	Type of working	Design Method	Explosives	Initiation	Goal of Fragmentation	Blast Records	Complexity	Robustness	Top Critical Variables
TAVARES PINHEIRO Jundiaí - SP	Hard Granite, high fracturation	Bench blasting with occasional pre-splitting	Semi-Empirical. Varying P.F. and drilling grid around pre-fixed values according to fracturation	Pumped emulsion with double booster downhole and uphole	Pyrotechnic conducting tube, micro-delays hole-to-hole, long delay downhole	D95=800 mm	4	N.A	N.A	N.A
INCOPEL Novo Hamburgo - RS	Columnar basalt, low to medium fracturation	Bench Blasting	Olofsson	Bottom Charge: Cartridge Emulsion; Column Charge: loose Anfo	Pyrotechnic conducting tube, micro-delays hole-to-hole	Maximum Diameter Feeding the crusher = 750 mm	11	4.91	71.6	Column Charge (20.67%) Total blast volume (19.45%) Primers density (18.27%) n. of holes (8.19%) n. of blasting caps (8.19%)
SULTEPA Novo Hamburgo - RS	Metamorphic Basalt, medium to high fracturation, with local branches of very high metamorphic degree	Bench Blasting	Semi-Empirical. Pre-Fixed P.F., varying drilling grid according to fracturation	Bottom Charge: Cartridge Emulsion; Column Charge: loose Anfo	Pyrotechnic conducting tube, micro-delays hole-to-hole, long delay downhole	Maximum Diameter Feeding the crusher = 800 mm	14	2.36	82.8	Hole length (24.46%) Bench Height (10.95%) Volume of competence (10.95%) Delay 2 (7.62%) Column Charge (6.19%)
Copelmi Butiá - RS	Coal Ore and Waste Schist Rock, very high fracturation	Strip Blasting of wide and thin layers, vertical holes with no subdrilling	Semi-Empirical. P.F. according to waste or ore presence, varying drilling grid according to fracturation	Bottom Charge: Cartridge Emulsion; Column Charge: loose Anfo	Pyrotechnic conducting tube, micro-delays hole-to-hole, no delay downhole	Maximum Diameter Feeding the crusher = 400 mm, low presence of fines	2020	6.80	80.1	Hole length (69.28%) Mean charge per hole (20.19%) Charged length (20.17%) Charge per delay (13.24%) Stemming (7.75%)

6 General analysis

In order to achieve a general overview of the structural links between the main variables in the bench blasting type of working, a C.A. has been carried on over a particular datasheet created including equal number of records sampled from each mine´s blasting databases. The degrees of complexity and robustness have not been taken into consideration for their lack of physical meaning, as this kind of datasheet does not represent a real system. On the other hand, the analysis provides meaningful results about the heuristic inter-connections of the variables in the kind of working “open pit bench blasting”. At this stage these correlations do not reflect theoretical methodologies or physical behavior of the blasts. They give instead an innovative overview of the engineering choices commonly used in the observed mines, revealing hidden structures that are implicitly contained in the executions of the workings.

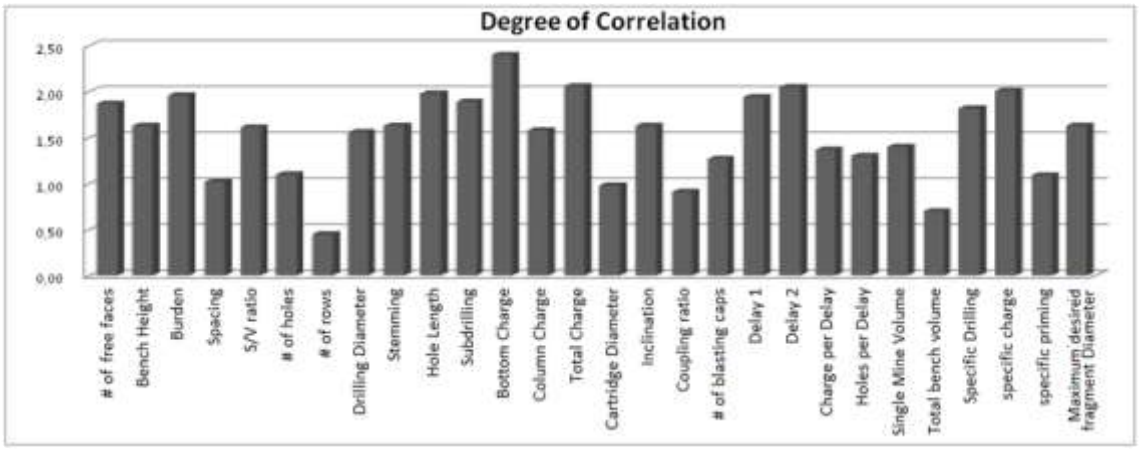

FIGURE 5: Degree of correlation of the variables

Figure 5 shows the degrees of inter-connection of each variable with the others, and in Table 3 the strongest interconnections are reported. Table 4 shows the main links of the variable considered goal of the fragmentation: the opening of the primary crusher. It can be observed that none of the charging parameters appear to be strongly correlated to the goal of fragmentation: this reflects a hidden structure and highlights a peculiar missing link, namely fragmentation, inside the engineering choices made in the analyzed mines, otherwise undetectable

7 Advanced analysis on the mine 3 database

In Mine 3, due to the high number of blast records, a further stage of the analysis has been carried on, analyzing the variation of complexity and robustness through varying classes of values of fundamental variables of the blast. The main characterizing variables have been chosen as:

- the total volume of the bench to be blasted (fig. 6), to look at the variation of the size of blast
- the powder factor (fig. 7), to look at the variation of the strength of the blast
- the type of material to be extracted

It can be observed (fig. 6) that, increasing the total volume of the blast, a general decrease of the complexity of the blast-system occurs; nevertheless, due to the according decrease of the critical complexity, robustness remains quite constant.

TABLE 3: Specific drilling is an index of hole density in the drilling pattern
S/V ratio (Spacing/Burden) is index of the shape of the drilling pattern

Variable	Degree of Correlation	Correlated variables and correlation index	
Bottom Charge	2.4	Spacing	0.64
		Burden	0.55
		Volume of Competence	0.55
		Specific Drilling	0.55
		Primers Density	0.56
Total Charge	2.06	Burden	0.59
		S/V Ratio	0.48
		Drilling Diameter	0.48
		Hole Length	0.54
		Subdrilling	0.46
		Column Charge	0.67
		Powder Factor	0.57
		Charge per Delay	0.44
		Volume of Competence	0.44
		Specific Drilling	0.38
Delay 2	2.05	Bench Height	0.51
		Drilling Diameter	0.40
		Stemming	0.51
		Hole Length	0.54
		Delay 1	0.79
		Burden	0.59
Powder Factor	2.01	Number of Free Faces	0.36
		S/V Ratio	0.50
		Total Charge	0.57
		Specific Drilling	0.45
		Burden	0.53

Variable	Degree of Correlation	Correlated variables and correlation index	
Burden	1.96	Number of Free Faces	0.48
		Drilling Diameter	0.58
		Column Charge	0.43
		Tot. Hole Charge	0.59
		Hole Length	0.54
		Bottom Charge	0.55
		Delay 1	0.40
		Delay 2	0.59
		Powder Factor	0.53
Delay 1	1.94	Bench Height	0.44
		Stemming	0.44
		Burden	0.40
		Delay 2	0.79
		Specific Drilling	0.61
Subdrilling	1.89	Number of Free Faces	0.37
		Total Charge	0.46
		Inclination	0.44
		Column Charge	0.35
		Specific Drilling	0.52
		Powder Factor	0.43
		Primers Density	0.35
		Maximum Desired Fragmentation	0.44
Number of free faces	1.87	Burden	0.48
		Spacing	0.39
		Drilling Diameter	0.34
		Hole Length	0.51

		Drilling Diameter	0.43
		Hole Length	0.49
		Subdrilling	0.43
		Column Charge	0.52
		n. of blasting caps	0.43
		Charge per Delay	0.51
		Primers Density	0.36
Hole Length	1.98	Number of Free Faces	0.51
		S/V Ratio	0.38
		Burden	0.54
		Tot. Hole Charge	0.54
		Hole Inclination	0.44
		Delay 2	0.54
		Specific Drilling	0.44
		Column Charge	0.42
		Powder Factor	0.49
		Maximum Desired Fragmentation	0.44

		Subdrilling	0.37
		Hole Inclination	0.51
		Volume of Competence	0.40
		Powder Factor	0.36
		Maximum Desired Fragmentation	0.51
Specific Drilling	1.82	Hole Length	0.44
		Inclination	0.44
		S/V Ratio	0.34
		Subdrilling	0.52
		Bottom Charge	0.55
		Total Charge	0.38
		Delay 1	0.61
		Volume of Competence	0.43
		Powder Factor	0.45
		Maximum Desired Fragmentation	0.44

TABLE 4: Correlations of the goal of fragmentation

Variable	**Degree of Correlation**	**Correlated variables and correlation index**	
Maximum Desired Fragmentation	1.63	Number of free faces	0.51
		Specific Drilling	0.44
		Subdrilling	0.44
		Hole length	0.44

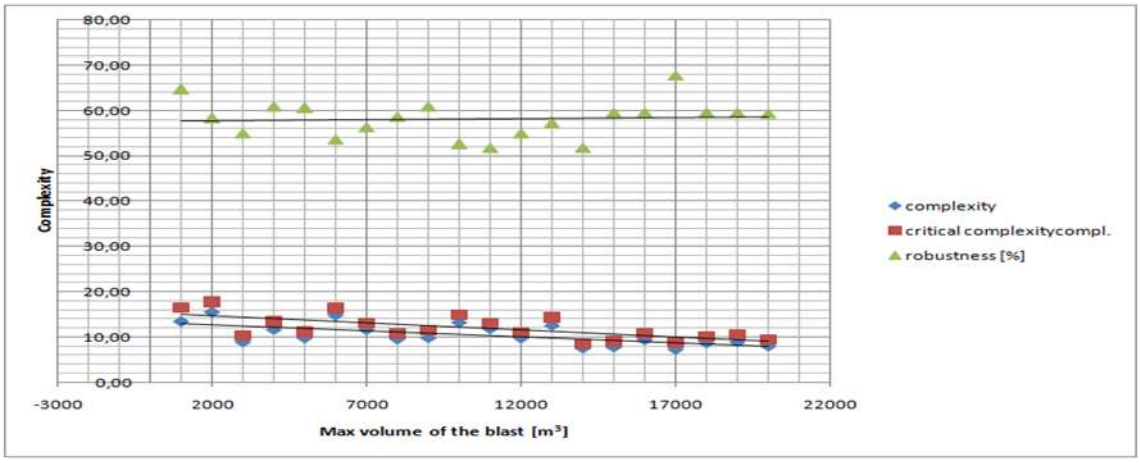

FIGURE 6: Variation of Complexity and Robustness Vs the volume of the blast

Looking at the specific charge (fig. 7), a peak of complexity is evident for the blasts with PF[1] between 0.1 and 0.2 kg/m3. This mine´s engineering office works with P.F. values normally between 0.10 and 0.22. The peak of complexity in this range is due to the increased structure that the standard type of blast has. Values of P.F. lower or higher than the standard range indicate exceptional operations out of the normal workings: this kind of blasts possess a lower structure due to their being less usual. Since the critical complexity follows the operative one proportionally, robustness remains almost unchanged, with an observable general decreasing trend. This means that stronger blasts result more critical and fragile than weak ones.

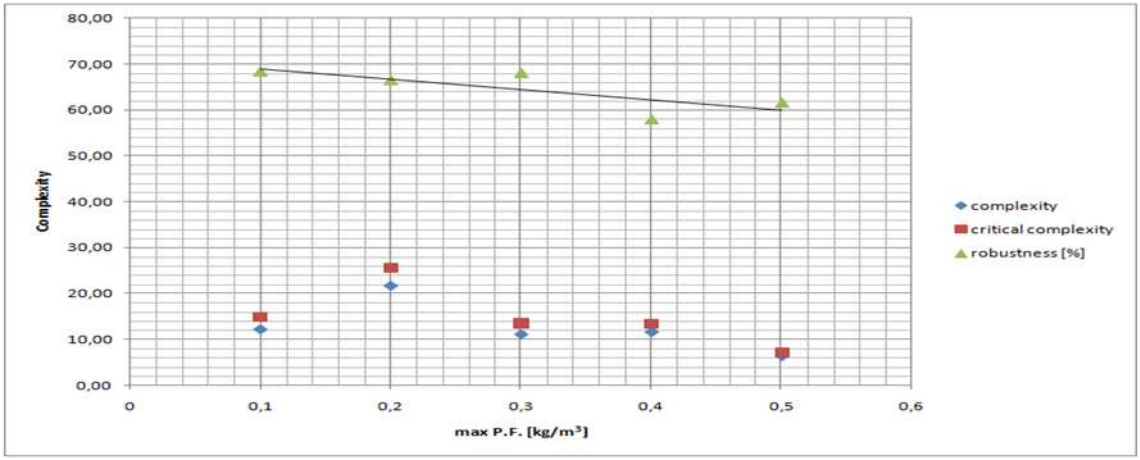

FIGURE 7: Variation of Complexity and Robustness Vs the powder factor

Looking at the three types of material to be extracted: waste, mixed waste and ore and coal ore (fig. 8), it appears clear that the blasts aimed to extract

[1] PF: *Powder Factor,* the quantity of explosive used per unit of rock blasted, usually in kg/m³.

productive ore, being meant to size the material to be processed through crushing and milling, possess high complexity and low robustness, resulting in a more fragile system; on the other hand the opening blasts in waste rock, aimed to uncover ore layers, are simpler works, not aiming at sizing material to further processing, and hence possess less structure and noise, thus resulting more robust.

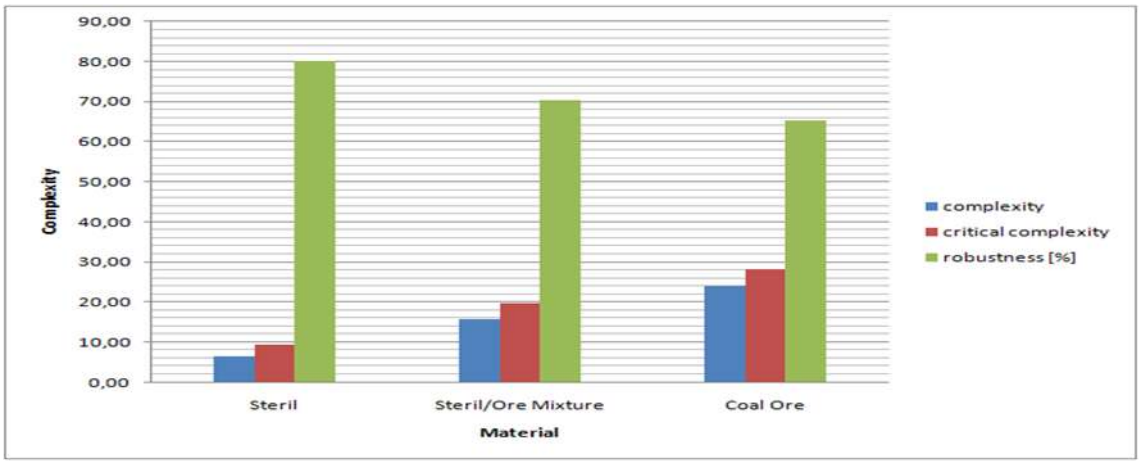

FIGURE8: Variation of Complexity and Robustness according to the type of material to be extracted

As shown by the results of this paragraph, an analysis of complexity and robustness performed over the blasting system results is a powerful operative and planning tool for the blast designer, allowing to understand where criticalities appear along the main parameters and showing the priorities to focus about to reduce production and safety risks.

8 Conclusions

Geological conditions are source of a high level of uncertainty in blasting practice due to geostructural conditions that lead to local site laws of cost. Local optimization by itself is operatively inefficient on high-productivity levels, and uncertainties in the environment (geology) cannot be avoided. Therefore we must learn to manage the complexity of the blast-system through the design, looking for a robust solution that is capable of withstanding unforeseen conditions without risk of undesired results. The present research led us to understand the complexity behaviours of some of the blast design systems. The conclusions that can be derived up to this moment are:

- a model-free approach to such a complex problem as the blasting process, based on image-analysis of data, allows understanding of hidden links and of the specific behavior of the blasting system;

- by including complexity as a characteristic of the system and using it as a qualitative indicator, criticalities can be detected where statistical analysis cannot investigate;
- blasting operations can be effectively understood, managed and improved using complexity and robustness as operational.
- the integration of the search for optimization with the management of robustness can lower the dependency of the rock blasting system from the uncertainty and criticality of its parameters .
- proper fragmentation data is of essence to advance the analysis and reach practical outcome.

Finally, when studying the rock blasting problem, the search for the absolute optimum, is rather inefficient as long as productivity on large scale is considered, since the geological environment is characterized by too many uncertainties that make it unfeasible to have just an optimum point valid for so many different applications. Also, since geology varies from site to site, and often from bench to bench on each site, the task of setting a robust method can grant better overall results in these varying environments, lowering costs and increasing the benefits such as predictability and safety of the operations.

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